LU TP 99-19
hep-ph/9907514

I : Chiral Perturbation for Kaons
II: The $\Delta I = 1/2$-rule in the Chiral Limit

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February 1, 2008

Abstract

I : Chiral Perturbation Theory is introduced and its applications to semileptonic and nonleptonic kaon decays are discussed.

II: The method of large N_c is used to calculate $K \to \pi\pi$ nonleptonic matrix elements, in particular the matching procedure between long and short-distance evolution that takes all scheme dependence correctly into account is discussed. Numerical results reproduce the $\Delta I = 1/2$ rule without the introduction of any free parameters.

1 Introduction

Chiral Perturbation Theory (CHPT) is a very large subject now so I will only discuss it briefly and then review the present status of its use in semileptonic and nonleptonic kaon decays. It has had several major successes in rare decays which are discussed in the contribution by Isidori [1]. The application to $K_L^0 \to \pi^+\pi^-e^+e^-$ is treated by Savage [2]. As described in the second part and in several other talks [3, 4], it is also very relevant in calculations of the nonleptonic matrixelements. In Section 2 I very briefly describe the underlying principles. The next section reviews the application to kaon semileptonic decays, this is one of the main playgrounds for CHPT and the area of some major successes. The use in kaon decays to pions is then discussed in Sect. 4. We treat the use of CHPT in simplifying matrixelement calculations in Sect. 4.1, predictions for $K \to 3\pi$ in Sect. 4.2, and chiral limit cancellations in B_6 in Sect. 4.3.

Section 5 constitutes part II of this talk. Here I describe how the large N_c method can take into account the scheme dependence of short-distance operators and first results[5].

2 Chiral Perturbation Theory

CHPT grew out of current algebra where systematically going beyond lowest order was difficult. The use of effective Lagrangians to reproduce current algebra results was well known and Weinberg showed how to use them for higher orders [6]. This method was improved and systematized by Gasser and Leutwyler in the classic papers [7] and proving that CHPT is indeed the low-energy limit for QCD using only general assumptions only was done by Leutwyler [8]. Recent lectures are [9].

The assumptions underlying CHPT are:

- Global Chiral Symmetry and its spontaneous breaking to the vector subgroup: $SU(3)_L \times SU(3)_R \to SU(3)_V$.
- The Goldstone Bosons from this spontaneous breakdown are the only relevant degrees of freedom, I.e. the only possible singularities.
- Analyticity, causality, cluster expansion and special relativity [8].

The result is then a systematic expansion in meson masses, quark-masses, momenta and external fields. The external field method allows to find the minimal set of parameters consistent with chiral symmetry and the rest is basically only unitarity. With current algebra and dispersive methods it is in principle also possible to obtain the same results but the method of Effective Field Theories is much simpler.

So for any application of CHPT two questions should be answered:

1. Does the expansion in momenta and quark masses converge ?
2. If higher orders are important then:
   - Can we determine all the needed parameters from the data ?
   - Can we estimate them if not directly obtainable.

3 Semileptonic decays

The application of CHPT to semileptonic decays has been reviewed in [10] and in [11]. Since then first results at order p^6 have appeared. The situation order by order is:

$\mathcal{L}_2$ 2 parameters: F_0, B_0 (+quark masses).

$\mathcal{L}_4$: 10+2 parameters [7] 7 are relevant; 3 more appear in the meson masses. In addition we also have the Wess-Zumino term and one-loop contributions.

$\mathcal{L}_6$: 90+4 parameters [12, 13]. In addition there are two-loop diagrams and one-loop diagrams with $\mathcal{L}_4$ vertices.

	F_π/F_0	F_K/F_π	$(F_K/F_\pi)^{(6)}$
p^2	1	1	—
p^4	1.07	1.22	—
p^6 set A	0.96 (1.08)	1.27 (1.30)	0.05 (0.08)
p^6 set A μ=0.9 GeV	0.96 (1.10)	1.30 (1.34)	0.08 (0.12)
p^6 set B	0.90 (1.02)	1.25 (1.28)	0.035 (0.06)

Table 1: Results for the ratios of F_π, F_K and the decay-constant in the chiral limit. The size of the p^6 only is in the last column.

3.1 General Situation

$\boldsymbol{p^2}$ Current Algebra : sixties
$\boldsymbol{p^4}$ One-loop 80's, early 90's
$\boldsymbol{p^6}$
- Estimates using dispersive and/or models: "done"
- Double Log Contributions: mostly done [15].
- Two-flavour full calculations: Done.
- Three flavour full calculations: few done, several in progress.

$\boldsymbol{e^2p^2}$ In progress.
Experiment Progress from DAPHNE, NA48, BNL, KTeV, ...

3.2 K_{l2}

These decays are used to determine F_K and test lepton universality by comparing $K \to \mu\nu$ and $K \to e\nu$. F_π is similarly determined from $\pi \to \mu\nu$. The theory is now known to NNLO fully in CHPT [16] (for F_π also [17]) The results are shown in Table 1 when the contributions from the p^6 Lagrangian are set to zero, i.e. $C_i^r = 0$, at the scale indicated. The numbers in brackets are the extended double log approximation of [15]. The inputs are $10^3 L_{i=4,10} = (-0.3, 1.4, -0.2, 0.9, 6.9, 5.5)$; $\mu = 0.77$ GeV unless otherwise indicated and for set A $10^3 L_{i=1,3} = (0.4, 1.35, -3.5)$ while for set B $10^3 L_{i=4,10} = (-0.3, 1.4, -0.2, 0.9, 6.9, 5.5)$. We see that the variation with the p^4 input is sizable and that the extended double log approximation gives a reasonable first estimate for the correction.

3.3 $K_{l2\gamma}$

In this decay there are two form-factors. The axial form-factor is known to p^4[18, 19] and a similar calculation for $\pi \to e\nu\gamma$[20] shows a 25% correction and a small dependence on the lepton invariant mass W^2. The vector form-factor is known to p^6[21] and has a 10 to 20 % correction in the relevant phasespace. The main interest in these decays is that it allows to test the anomaly and its sign as well as the $V-A$ structure of the weak interactions.

	p^2	p^4	Ext. double log	Experiment
f_+	1	-0.0023	$-0.005 \to 0.004$	input for V_{us}
λ_+	0	0.031	$-0.006 \to -0.0044$	0.029 ± 0.002
λ_0	0	0.017	$0.003 \to 0.009$	0.025 ± 0.006 $K^0_{\mu 3}$
				0.006 ± 0.007 $K^+_{\mu 3}$
λ'_+	0	small	$0.0002 \to 0.0003$	
λ'_0	0	small	$0.0001 \to 0.0002$	

Table 2: CHPT and experimental results for K_{l3} decays.

3.4 K_{l2ll}

In these decays there are three vector and one axial form-factor. The vector ones are known to p^4 [19] and the axial one to p^6 [21]. Especially the decays with $e\nu_e$ in the final state are strongly enhanced over Bremsstrahlung. Since my last review [11] there is a new limit from BNL E787 [22] of $B(K^+ \to e^+\nu\mu^+\mu^-) \leq 5 \cdot 10^{-7}$. All data are in good agreement with CHPT.

3.5 K_{l3}

These decays, $K^{+,0} \to \pi^{0,-}\ell^+\nu$, are our main source of knowledge of the CKM element V_{us}. It is therefore important to have as precise predictions as possible. The form-factors

$$\langle \pi(p')|V_\mu^{4-i5}|K(p)\rangle = \frac{1}{\sqrt{2}}\left[(p+p')_\mu f_+(t) + (p-p')_\mu f_-(t)\right] \qquad (1)$$

are usually parametrized by $f_+(t) \approx f_+(0)\,[1+\lambda_+ t/m_\pi^2]$ and $f_0(t) \equiv f_+(t) + t f_-(t)/(m_K^2 - m_\pi^2) \approx f_+(0)\,[1+\lambda_0 t/m_\pi^2]$.

The CHPT calculation at order p^4 fits these parametrizations well[23]. The agreement with data is quite good except for the scalar slope where there is disagreement between different experiments. The extended double log calculation[15] has small quadratic slopes, λ'_+ and λ'_0, and small corrections to the linear slopes. This, as shown in Table 2, is good news for improving the precision of V_{us}. f_+ is shown for $K^0 \to \pi^- e^+\nu$ where isospin breaking is smallest.

3.6 $K_{l3\gamma}$

These decays have been calculated in CHPT to p^4 in [19]. There are 10 formfactors and after a complicated interplay between all the various terms the final corrections to tree level are small even though individual form factors have large corrections. E.g. first adding tree level, then p^4 tree level and finally p^4 loop level contributions changes $B(K^+_{e3\gamma})$ with $E_\gamma \geq 30$ MeV

	$F(0)$	$\lambda F(0)$	$G(0)$
p^2	3.74	—	3.74
p^4	set B; fit to L_1, L_2, L_3		
dispersive	set A; fit to L_1, L_2, L_3		
p^6 set A	0.86	0.38	-0.15
p^6 set A $\mu = 0.9\ GeV$	1.13	0.51	-0.20
p^6 set B	0.75	0.17	-0.04
experiment	5.59 ± 0.14	0.45 ± 0.11	4.77 ± 0.27

Table 3: CHPT, dispersive, partial p^6 [15] and experimental results for K_{l4}.

and $\theta_{\ell\gamma} \geq 20^o$ from 2.8 10^{-4} via 3.2 10^{-4} to 3.0 10^{-4}. Notice that $F_K/F_\pi = 1.22$ so agreement with tree level at the 10% level is a good test of CHPT at order p^4.

Recent new results of $B(K^0_{e3\gamma}) = (3.61 \pm 0.14 \pm 0.21)\ 10^{-3}$ [24](NA31) and $B(K^0_{\mu3\gamma}) = (0.56 \pm 0.05 \pm 0.05)\ 10^{-3}$ [25] (NA48) are in good agreement with the theory results[19] of $(3.6 \to 4.0 \to 3.8)\ 10^{-3}$ and $(0.52 \to 0.59 \to 0.56)\ 10^{-3}$ respectively. The three numbers correspond to the contributions included as above.

3.7 K_{l4}

In these decays, $K \to \pi\pi\ell\nu$, there are four form-factors, F, G, H, R as defined in [10, 26]. The R form factor can only be measured in $K_{\mu4}$ decays and is known to p^4[26]. F and G were calculated to p^4 in [27] and improved using dispersion relations in [26]. The main data come from [28] ($K \to \pi^+\pi^-e^+\nu$) and [29] ($K_L \to \pi^\pm\pi^0e^\mp\nu$). The form factors were parametrized as $X = X(0)(1 + \lambda(s_{\pi\pi}/(4m_\pi^2) - 1))$ with the same slope for $X = F, G, H$. $H(0) = -2.7 \pm 0.7$ is a test of the anomaly in both sign and magnitude, see [21] and references therein. The other numbers are the main input for L_1^r, L_2^r and L_3^r. In table 3 I show the tree level results, which expression, the p^4 or dispersive improved, to determine $L^r_{1,2,3}$ of set A and B given in Sect. 3.2, and the extended double log estimate of p^6[15]. The results of the latter show similar patterns as the dispersive improvement. The full p^6 calculation is in progress and if the results are as indicated by the extended double log approximation a refitting of p^4 constants will be necessary. This is important since in these decays and in pionium decays the $\pi\pi$ phaseshifts will be measured accurately and their main theory uncertainty is the values of these constants. A useful parametrization to determine these phases from K_{l4} can be found in [30] as well as further relevant references.

4 Nonleptonic decays

For rare decays see [1], here only $K \to 0, \pi, \pi\pi, \pi\pi\pi$ are discussed. The lowest order Lagrangian contains three terms with parameters G_8, G_{27}, G_8' in the notation of [31]. The term with G_8', the weak mass term, contributes to processes with photons at lowest order and otherwise at NLO[31]. The NLO lagrangian contains about 30 parameters for the octet, denoted by E_i, and twenty-seven, denoted by D_i, representation of $SU(3)_L$ [32, 33].

4.1 $K \to \pi, K \to 0 \leftrightarrow K \to \pi\pi$

As shown in [31] the method of [34] can be extended to p^4 using well defined off-shell Green functions of pseudo-scalar currents. Except for one E_i and one D_i all the necessary ones can be obtained from $K \to \pi$ transitions[1]. To $K \to \pi\pi$ at order p^4 7 E_i and 6 D_i contribute in addition to the three couplings of lowest order. Of these 16 constants we can determine 14 from the much simpler K to π and vacuum transitions. This allows thus a more stringent test of various models than possible from on-shell $K \to \pi\pi$ alone. Models like factorization etc. will probably be needed in the foreseeable future to go to $K \to 3\pi$ and various rare decays.

4.2 CHPT for $K \to \pi\pi$ and $K \to \pi\pi\pi$

These decays were calculated to p^4 [35], relations between them clarified in [36] and some p^6 estimates to them were performed in [37].

The main problem is to find experimental relations after all parameters are counted. To order p^2 we have 2(1) and to p^4 7(3). The number in brackets refers to the $\Delta I = 1/2$ observables only. As observables (after using isospin) we have 2(1) $K \to \pi\pi$ rates and 2(1)(+1) $K \to \pi\pi\pi$ rates. We have 3(1)(+3) linear and 5(1)(+5) quadratic slopes. The (+i) indicates the phases, in principle also measurable and predicted but not counted here. 12 observables and 7 parameters leave five relations to be tested. The fits and results are shown in Table 4 where we have also indicated which quantities are related. See [36, 38] for definitions and references. The new CPLEAR[39] data improve the precision slightly. $K \to \pi\pi$ rates are always input. It is important to tests these relations directly, the agreement at present is satisfactory but errors are large.

CP-violation in $K \to 3\pi$ will be very difficult to detect. The strong phases needed to interfere with are very small, see [37] and references therein. E.g. $\delta_2 - \delta_1$ in $K_L \to \pi^+\pi^-\pi^0$ is predicted to be -0.083 and the experimental result is only -0.33 ± 0.29. Asymmetries are expected to be of order 10^{-6} so we can only expect to improve limits in the near future.

[1] Using $K \to 0$ allows to obtain two more constants than given in [31].

variable	p^2	p^4	experiment
α_1	74	input(1)	91.71 ± 0.32
β_1	-16.5	input(2)	-25.68 ± 0.27
ζ_1	$-$	$-0.47 \pm 0.18(1)$	-0.47 ± 0.15
ξ_1	$-$	$-1.58 \pm 0.19(2)$	-1.51 ± 0.30
α_3	-4.1	input(3)	-7.36 ± 0.47
β_3	-1.0	input(4)	-2.42 ± 0.41
γ_3	1.8	input(5)	2.26 ± 0.23
ξ_3	$-$	$0.092 \pm 0.030(4)$	-0.12 ± 0.17
ξ_3'	$-$	$-0.033 \pm 0.077(5)$	-0.21 ± 0.51
ζ_3	$-$	$-0.011 \pm 0.006(3)$	-0.21 ± 0.08

Table 4: The predictions and experimental results for the various $K \to 3\pi$ quantities. Numbers in brackets refer to the related quantities.

4.3 B_6 in the chiral limit

In the usual definitions of B_i factors in nonleptonic decays

$$B_6 \equiv \frac{\langle \mathrm{out}|Q_6|\mathrm{in}\rangle}{\langle \mathrm{out}|Q_6|\mathrm{in}\rangle_{\mathrm{factorized}}} \tag{2}$$

the denominator needs to be well defined. This is *not* true for B_6 in the chiral limit. The factorizable denominator contains the scalar radius which is infinite in full chiral limit. This can be seen in the CHPT calculation[5].

$$G_8\Big|_{Q_6\mathrm{fact}} = -\frac{80 C_6(\mu) B_0^2(\mu)}{3F_0^2}\left[L_5^r(\nu) - \frac{3}{256\pi^2}\{2\ln\frac{m_L}{\nu} + 1\}\right] \tag{3}$$

Here ν is the CHPT scale and m_L the meson mass, we can see that $G_{8fact} \longrightarrow \infty$ for $m_L \to 0$.

The nonfactorizable part has precisely the same divergence so that in the sum it cancels. Thus when calculating B_6 care must be taken to calculate factorizable and nonfactorizable consistently so this cancellation that is required by chiral symmetry takes place and does not inflate final results.

5 The X-boson method and the $\Delta I = 1/2$ rule in the chiral limit.

In this section I shortly describe how in the context of the large N_c method [3, 4, 40] after the improvements of the momentum routing[41] also the scheme dependence[42, 43] can be described. Other relevant references to the problem of nonleptonic matrix elements are [44].

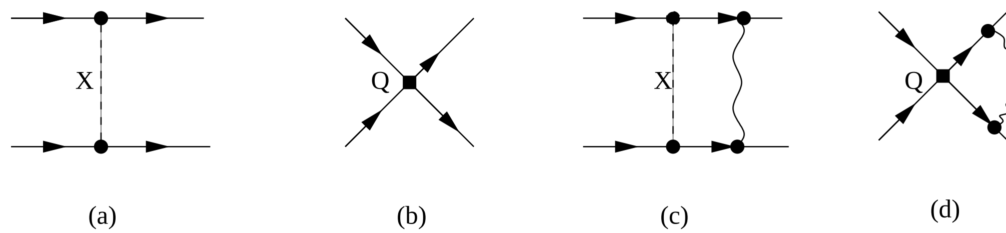

Figure 1: The diagrams needed for the identification of the local operator Q with X-boson exchange in the case of only one operator and no Penguin diagrams. The wiggly line denotes gluons, the square the operator Q and the dashed line the X-exchange. The external lines are quarks.

The basic underlying idea is that we have more experience in hadronizing currents. We therefore replace the effect of the local operators of $H_W(\mu) = \sum_i C_i(\mu)Q_i(\mu)$ at a scale μ by the exchange of a series of colourless X-bosons at a low scale μ. Let me illustrate the procedure in a simpler case of only one operator and neglecting penguin contributions. In the more general case all coefficients become matrices.

$$C_1(\mu)(\bar{s}_L\gamma_\mu d_L)(\bar{u}_L\gamma^\mu u_L) \Longleftrightarrow X_\mu \left[g_1(\bar{s}_L\gamma^\mu d_L) + g_2(\bar{u}_L\gamma^\mu u_L)\right] . \qquad (4)$$

Colour indices inside brackets are summed over. To determine g_1, g_2 as a function of C_1 we set matrix elements of C_1Q_1 equal to the equivalent ones of X-boson exchange. This must be done at a μ such that perturbative QCD methods can still be used and thus we can use external states of quarks and gluons. To lowest order this is simple. The tree level diagram from Fig. 1(a) is set equal to that of Fig. 1(b) leading to $C_1 = g_1g_2/M_X^2$ .At NLO diagrams like Fig. 1(c) and 1(d) contribute as well leading to

$$C_1\left(1+\alpha_S(\mu)r_1\right) = \frac{g_1g_2}{M_X^2}\left(1+\alpha_S(\mu)a_1+\alpha_S(\mu)b_1\log\frac{M_X^2}{\mu^2}\right) . \qquad (5)$$

The left-hand-side (lhs) is scheme-independent. The right-hand-side can be calculated in a very different renormalization scheme from the lhs. The infrared dependence of r_1 is present in precisely the same way in a_1 such that g_1 and g_2 are scheme-independent and independent of the precise infrared definition of the external state in Fig. 1.

One step remains, to calculate the matrix element of X-boson exchange between meson external states. The integral over X-boson momenta we split in two

$$\int_0^\infty dp_X \frac{1}{p_X^2-M_X^2} \Longrightarrow \int_0^{\mu_1} dp_X \frac{1}{p_X^2-M_X^2} + \int_{\mu_1}^\infty dp_X \frac{1}{p_X^2-M_X^2} . \qquad (6)$$

The second term involves a high momentum that needs to flow back through quarks or gluons and leads through diagrams like the one of Fig. 1(c) to a

four quark-operator with a coefficient

$$\frac{g_1 g_2}{M_X^2}\left(\alpha_S(\mu_1)a_2 + \alpha_S(\mu_1)b_1 \log\frac{M_X^2}{\mu^2}\right) . \tag{7}$$

The four-quark operator needs to be evaluated only in leading order in $1/N_c$. The first term in (6) we have to evaluate in a low-energy model with as much QCD input as possible. The μ_1 dependence cancels between the two terms in (6) if the low-energy model is good enough. The coefficients r_1, a_1 and a_2 give the correction to the factorization used in previous $1/N_c$ calculations.

It should be stressed that in the end all dependence on M_X cancels out. The X-boson is a purely technical device to correctly identify the four-quark operators in terms of well-defined products of nonlocal currents.

5.1 Numerical results

We now use the X-boson method with r_1 as given in [42] and $a_1 = a_2 = 0$, the calculation of the latter is in progress, and $\mu = \mu_1$. For B_K we can extrapolate to the pole both for the real case ($\hat{B}_K$) and in the chiral limit ($\hat{B}_K^\chi$). For $K \to \pi\pi$ we can get at the values of the octet (G_8), weak mass term (G_8') and 27-plet (G_{27}) coupling. We obtain $\hat{B}_K^\chi = 0.25$–0.4 ;

$$\hat{B}_K = 0.69 \pm 0.10\,;\; G_8 = 4.3\text{–}7.5\,;\; G_{27} = 0.25\text{–}0.40 \text{ and } G_8' = 0.8\text{–}1.1\,. \tag{8}$$

The experimental values are $G_8 \approx 6.2$ and $G_{27} \approx 0.48$ [5, 35].

In Fig. 2 the μ dependence of G_8 is shown and in Fig. 3 the contribution from the various different operators. If we look inside the numbers we see that B_6 defined with only the large N_c term in the factorizable part, is about 2 to 2.2 for μ from 0.6 to 1.0 GeV.

6 Conclusions

CHPT is doing fine in kaon decays, especially in the semileptonic sector where several calculations at p^6 are now in progress. In the nonleptonic sector it provides several relations in $K \to 3\pi$ decays. Testing these is an important part since it tells us how well p^4 works in this sector. CHPT can also help in simplifying and identifying potentially dangerous parts in the calculations of nonleptonic matrix elements.

The large N_c method allows to include the scheme dependence appearing in short-distance operators and when then all long-distance constraints from CHPT and some other input are used encouraging results are obtained for $K \to \pi\pi$ decays in the chiral limit.

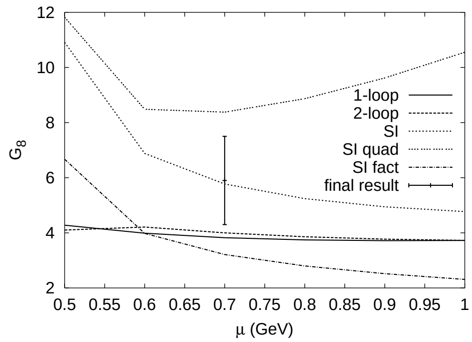

Figure 2: G_8 as a function of μ using the ENJL model and Wilson coefficients at one-loop, at 2-loop with and without the r_1 (SI). The factorization (SI fact) and the approach of [3] (SI quad) are shown for SI also.

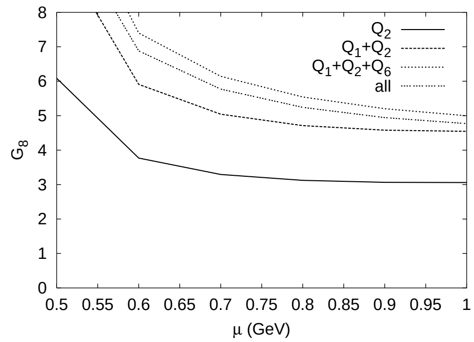

Figure 3: The composition of G_8 as a function of μ. Shown are Q_2, $Q_1 + Q_2$, $Q_1 + Q_2 + Q_6$ and all 6 Q_i. The coefficients r_1 are included in the Wilson coefficients.

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